Quantum Sensing of Mechanical Motion with a Single InAs Quantum Dot

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Abstract: *Coupling quantum systems to mechanical motion is attractive for fundamental science and sensing. We have embedded a semiconductor quantum dot (QD) inside a mechanical resonator that provides a versatile platform for advances in this area. Driving mechanical motion produces large changes in the QD optical transitions as well as the spin degree of freedom, indicating strong potential for quantum sensing.*

Keywords: Quantum Dots; MEMS; Spin; Sensing

Introduction

In recent years, there has been significant interest in taking advantage of properties of quantum mechanics, primarily superpositions and entanglement, to make fundamental improvements to computation, communication, and measurement. Atomic systems have long been utilized for precision time-keeping and for sensing other aspects of the environment due to their high coherence and the ability to precisely control them. There is now a strong motivation to introduce “artificial atoms” into solid state systems, with coherence properties similar to atoms but having many such “atoms” integrated into devices with properties that may be engineered.

A number of solid state quantum systems have been considered for sensing motion of mechanical resonators, including point defects in diamond [1], superconducting quantum bits (qubits) [2], and semiconductor QDs [3]. The key features that make QDs promising are the ability to engineer the properties of the quantum dots through growth and electrical tuning as well as their excellent optical properties. A few studies have now examined the effect of static or dynamic mechanical motion on the optical transitions of QDs [4]–[8], which occur due to strain in the lattice. While the changes in optical transitions can be quite significant, they do not take full advantage of the quantum coherence of QDs, which is far superior when using the spin degree of freedom. Spin coherence times of electrons or holes in QDs are in the μs range, over three orders of magnitude longer than optical coherence times. Ultrafast optical pulses have been used to manipulate the spin state within a single QD as well as the entangled state of two spins in coupled QDs [9].

We have successfully integrated a quantum system composed of a single InAs QD into a mechanical resonator in order to sense mechanical motion through strain. An electrical diode within the resonator enables charging of the QDs, which allows measurements of how the optical transitions and the spin states change in the presence of mechanical motion.

System

The sample is grown by molecular beam epitaxy on a GaAs substrate. A 950 nm layer of $Al_{0.7}Ga_{0.3}As$ is grown first, followed by a 180 nm n-i-n-i-p diode structure with the InAs QDs grown closer to the lower n-type layer (see Fig. 1). The InAs QDs are a few nm in height and about 10-20 nm in diameter and are distributed randomly in the lateral dimensions. The bias on the diode controls the charge state of the QD, with one electron at a time tunneling into the QD as the bias is increased [10], [11]. The sacrificial layer of AlGaAs is included in order to undercut the structure and produce suspended mechanical resonators and photonic cavities, as displayed in Fig. 1.

Figure 1. QD sample structure showing the diode within the suspended membrane.

Several types of mechanical resonators have been fabricated that couple the integrated QDs to mechanical motion through strain. Both photonic crystal membranes and tuning fork structures have been fabricated, with examples displayed in Fig. 2(a,b). Photonic crystal cavities have flexural modes that induce strain for QDs, and they also improve the collection of photons from the QDs for enhanced readout. Tuning fork structures can be used to concentrate strain at the position of QDs and allow very large displacements and strain amplitudes. The strain induced by bending these structures in and out of the plane is zero at the vertical center of the membrane and maximum at the top and bottom (one side compressive and

one side tensile). TheQDs have been shifted in the growth direction by 30 nm in order to give finite strain.

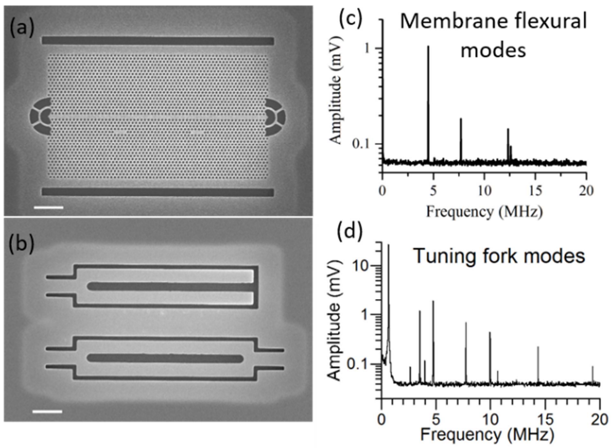

Figure 2. Scanning electron microscope image of (a) photonic crystal structure and (b) tuning fork resonators. The scale bar represents 2 μm. (c,d) Laser reflectivity measurement of mechanical spectra of a photonic crystal membrane and tuning fork.

The mechanical modes of these structures are measured by optically driving with an amplitude modulated laser and probing changes in the reflectivity of a second laser. Interference between reflection from the substrate and reflection from the membrane results in changes in the reflectivity when displacement occurs. Figure 2(c,d) display the mechanical resonances that occur as the drive frequency is varied in the MHz range. The lowest mode for the photonic crystal membrane at about 4.5 MHz corresponds to the entire membrane flexing up and down, with higher modes having increasing number of nodes. The lowest mode of the tuning fork at 1.4 MHz corresponds to the entire tuning fork moving up and down out of the page and can have a very large amplitude. At maximum laser drive, the displacement of the end of the tuning fork is estimated at ±300 nm, resulting in an estimated strain of ~3 $\times 10^{-4}$.

Results

We have measured the effect of mechanical motion on QDs in these structures by optically driving the mechanical resonator while synchronously measuring the high resolution optical emission of the QDs. All measurements were performed at a temperature of about 4 K. In photonic crystal membranes, the response of a series of QDs along the length of a waveguide was measured to determine the optimum position for peak sensitivity. The photonic crystal waveguide was similar to that in Fig. 2(a) but with the membrane clamped on all four sides. High resolution photoluminescence (PL) spectra were obtained by sending emission through a scanning Fabry-Perot cavity with a resolution of 9 μeV and then through a monochromator to a single photon counting module (SPCM). Time-correlated photon counting was used to measure PL as a function of time, synchronized to the mechanical drive laser. Fig. 3(a) displays a map of PL for a QD near the center of the waveguide, while driving the lowest flexural mode of the membrane at 4.5 MHz. The emission energy shifts sinusoidally with an amplitude of 27 μeV due to motion induced strain. This measurement was performed for a series of QDs along the length of the waveguide for three different flexural modes. The energy shift is plotted as a function of position in Fig. 3(b), showing a maximum near the center and a reduction in amplitude to near zero moving toward either end, consistent with the expected strain profile for the lowest mode. For the 2nd mode at 7.75 MHz, the energy shift is near zero at the center and increases in amplitude moving toward the edges. The change in sign across the center is determined by the phase of the shift in energy. This behavior is consistent with the node in the center of the membrane for the 2nd mode. Similarly, the 3rd mode has two nodes in the energy shift. Interestingly, the maximum energy shifts for the higher order modes are within a factor of 2.5 of those for the lowest mode. In contrast, measurements of displacement using laser reflectivity give amplitudes more than an order of magnitude weaker for 2nd and 3rd modes compared to the fundamental. We expect that this difference is due to different scaling between strain and displacement as a function of frequency and the nanometer scale of the QD sensor.

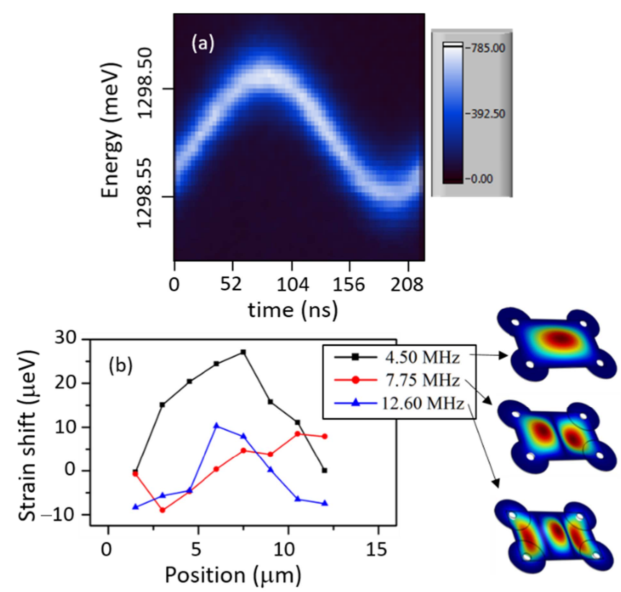

Figure 3. (a) Emission as a function of time and energy for a QD near the center of a photonic crystal waveguide, measured while driving the lowest flexural mode. (b) Strain induced shift for a series of QDs positioned along the length of the waveguide for three flexural modes. The images on the right display displacement of these modes as color maps.

In tuning forks, we find that the for fundamental mode, in which the entire structure vibrates like a diving board, the effect on a QD is very strong, giving rise to shifts in the QD emission energy more than two orders of magnitude larger than the natural linewidth. In order to determine the effect of motion/strain on the *spin* states of the QD, a magnetic field is applied perpendicular to the growth direction. Figure 4(a) displays the energy level diagram for a QD charged with one resident electron. The two lower levels represent the two spin states of the electron. The two higher energy states consist of two electrons and one hole, with the energy difference only determined by the hole spin. Four optical transitions are allowed, with differences in transition energies giving electron and hole spin splittings. Figure 4(b) shows PL from a QD in an undriven tuning fork showing all four transitions. The QD position is near the narrow neck connecting the fork to the sample, giving maximum strain.

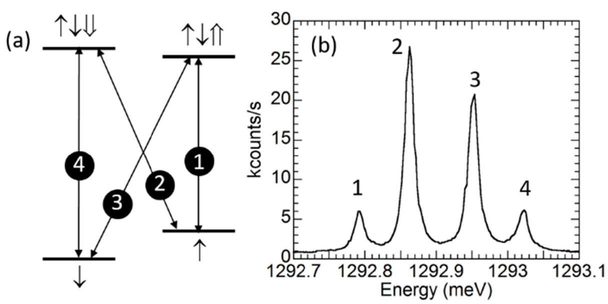

Figure 4. (a) Energy level diagram for a QD charged with a single electron in a magnetic field. Single arrows represent electrons and double arrows represent holes. (b) PL from a single QD in a tuning fork with a 6 T magnetic field. Exciting with 31 μW at 932 nm

Figure 5(a) displays the PL from all four of these transitions as a function of time when the tuning fork is driven at 683 kHz, the lowest vibrational mode. Each emission line shifts by ±295 μeV, with the PL amplitude decreasing at the extrema. This decrease is likely due to the charge state becoming unstable at such large shifts. The electron and hole spin splittings are obtained from this data by fitting the four lines at each time and taking differences. The difference between lines 4 and 2 or 3 and 1 gives the electron spin splitting, while the difference between 4 and 3 or 2 and 1 gives the hole spin splitting. The electron and hole spin splittings are plotted in Fig. 5(b) as a function of time, displaying a clear oscillation in the hole spin splitting by ±10% of its undriven value with no clear change in the electron spin splitting. This measurement has been repeated for many QDs in tuning forks, showing similar results with some variation in the amplitude of the hole spin shift.

Conclusion

We have demonstrated the integration of a solid state quantum system with mechanical resonators. The ability to control the charge state of the QDs as well as enhance the optical properties using cavities makes this platform particularly attractive. Large shifts in the optical transitions have been observed when the mechanical resonances are driven, consistent with strain induced by motion. In photonic crystal membranes, the response to motion has been mapped out spatially along one direction for the fundamental flexural mode and two higher order modes, showing positions of maximum response. The response of the QDs to motion at higher frequencies also appears to indicate an advantage of this nanoscale strain sensor over more widely-used displacement measurements that rapidly lose amplitude at higher frequencies.

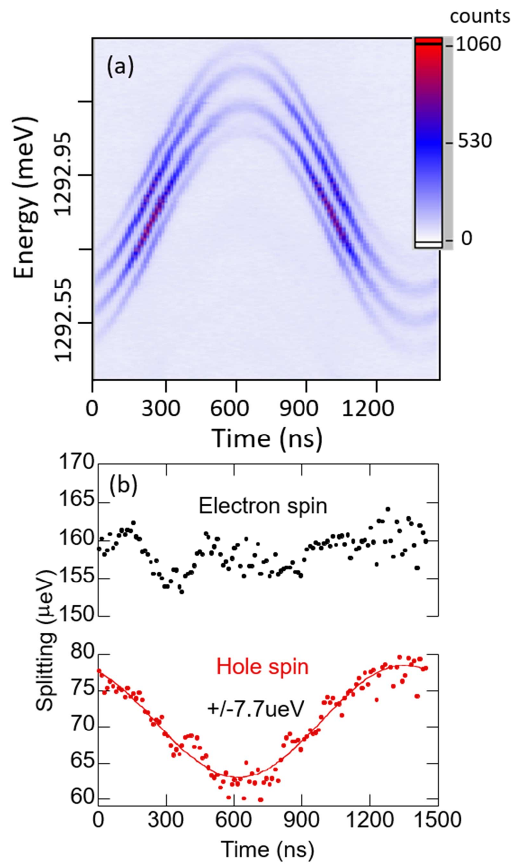

Figure 5. (a) QD emission lines as a function of emission energy and time at 6 T, while driving the lowest mechanical resonance of the tuning fork. (b) The electron and hole spin splittings as a function of time, with a solid red line indicating a sinusoidal fit to the hole data.

We have also demonstrated coupling of a spin in a QD to mechanical motion for the first time. While the electron spin showed no measurable response to motion through strain, the hole spin showed a strong response of about ~7 THz/strain, based on the estimated strain. This is roughly 3 orders of magnitude higher than that measured for defect spins in diamond and SiC [1], [12]. We expect that the difference in response between electrons and holes is in part due to the strain-dependent heavy hole/light hole mixing that affects the hole g-factor. While this work demonstrates the response of the hole spin to motion

through strain, the hole spin coherence here lasts only as long as the optical lifetime of about 1 ns. Samples that inject a single hole into the QD can be used to take full advantage of the hole spin coherence of ~1 μs. Further enhancement of the response to strain and coherence time should also be possible using the entangled states of coupled QDs in similar structures.

We anticipate that this research will enable a new class of precision sensors based on solid state artificial atoms integrated into semiconductor devices that are engineered to be sensitive to one aspect of the environment. High sensitivity to mechanical motion is relevant to a number of DOD interests, including accelerometry for inertial navigation, and gravity gradiometry for detecting shielded nuclear materials. This research also has the potential to revolutionize the growing field of coupling quantum systems to macroscopic systems for fundamental science and improved functionality.

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